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## REPORT DOCUMENTATION PAGE

Form Approved  
OMB NO. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comment regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE

12/17/2001

3. REPORT TYPE AND DATES COVERED

12/1/95 - 11/30/01 Final Report

4. TITLE AND SUBTITLE

MURI -- Final Progress Report

Contract Number DAAH04-96-1-0001 "Low Power/Low Noise Electronics" 35003EL-MUR

5. FUNDING NUMBERS

05003EL-MUR

DAAH04-96-1-0001

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8. PERFORMING ORGANIZATION  
REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Army Research Office

P. O. Box 12211

Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING  
AGENCY REPORT NUMBER

35003.103-EL-MUR

11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Army communication systems have several major limitations, including limited bandwidth, low throughput, dependence upon terrestrial line-of-sight, lack of full mobility and limited support for intelligence and imagery requirements. Additional requirements include low probability of intercept, jam resistant, multi-frequency systems and low power, weight and cost and small size.

The purpose of this program was to address the fundamental limitations of these issues from an overall systems objective and develop appropriate modulation techniques, analog and digital devices and circuits in order to optimize the performance and significantly lower power consumption.

14. SUBJECT TERMS

20020125 314

15. NUMBER OF PAGES

28

16. PRICE CODE

17. SECURITY CLASSIFICATION  
OF REPORT

UNCLASSIFIED

18. SECURITY CLASSIFICATION  
OF THIS PAGE

UNCLASSIFIED

19. SECURITY CLASSIFICATION  
OF ABSTRACT

UNCLASSIFIED

20. LIMITATION OF ABSTRACT

UL

NSN 7540-01-280-5500

Standard Form 298 (rev. 2-89)  
Prescribed by ANSI Std. Z39-18  
200-102

## Foreword

Army communication systems have several major limitations, including limited bandwidth, low throughput, dependence upon terrestrial line-of-sight, lack of full mobility and limited support for intelligence and imagery requirements. Additional requirements include low probability of intercept, jam resistant, multi-frequency systems and low power, weight and cost and small size.

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## Statement of the Problem

Army communication systems have several major limitations, including limited bandwidth, low throughput, dependence upon terrestrial line-of-sight, lack of full mobility and limited support for intelligence and imagery requirements. Additional requirements include low probability of intercept, jam resistant, multi-frequency systems and low power, weight and cost and small size.

The purpose of this program was to address the fundamental limitations of these issues from an overall systems objective and develop appropriate modulation techniques, analog and digital devices and circuits in order to optimize the performance and significantly lower power consumption.

The emphasis was placed on systems which have the following characteristics:

- Low Probability of Intercept
- Jam Resistant
- Multiple-Access Capability
- Multi-Frequency Systems
- Low Power

These lead to modulation techniques that trade bandwidth efficiency (bits/sec./Hz) for energy efficiency (joules/bit). These techniques are generally called Spread-Spectrum Modulation.

A typical communication system is shown in Figure 1. In order to minimize power consumption a system approach is needed to investigate tradeoffs. The various elements and interactions required are shown in Figure 2. These various elements were addressed by several faculty members and graduate students and the major results are described in following sections of this report.

## TYPICAL SUPERHETERODYNE TRANSCEIVER

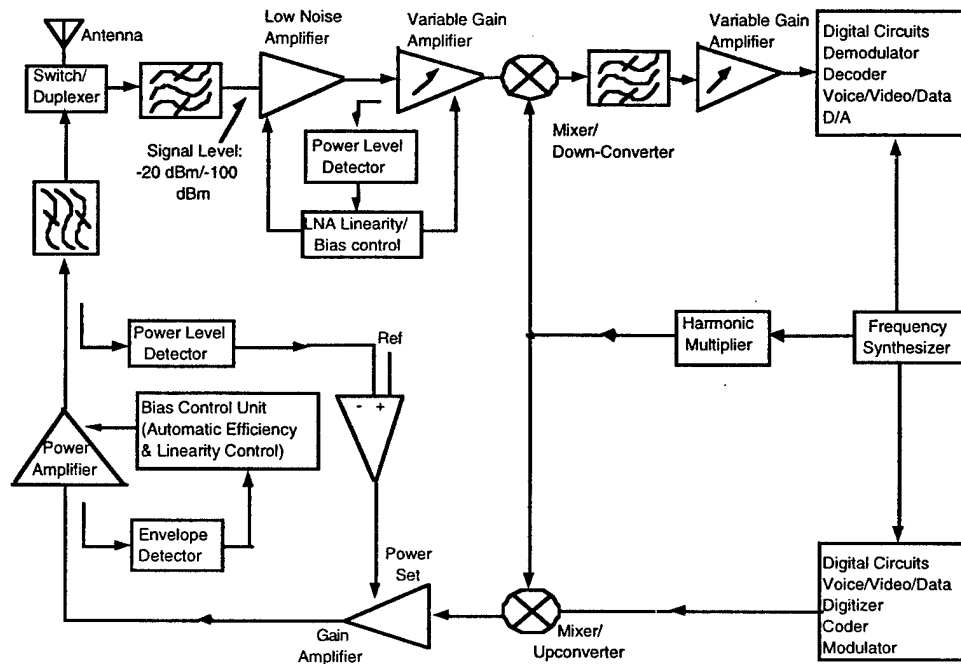


Figure 1

## Minimum Energy/Low Power Electronics

A System Approach is needed to investigate tradeoffs and optimize system performance.

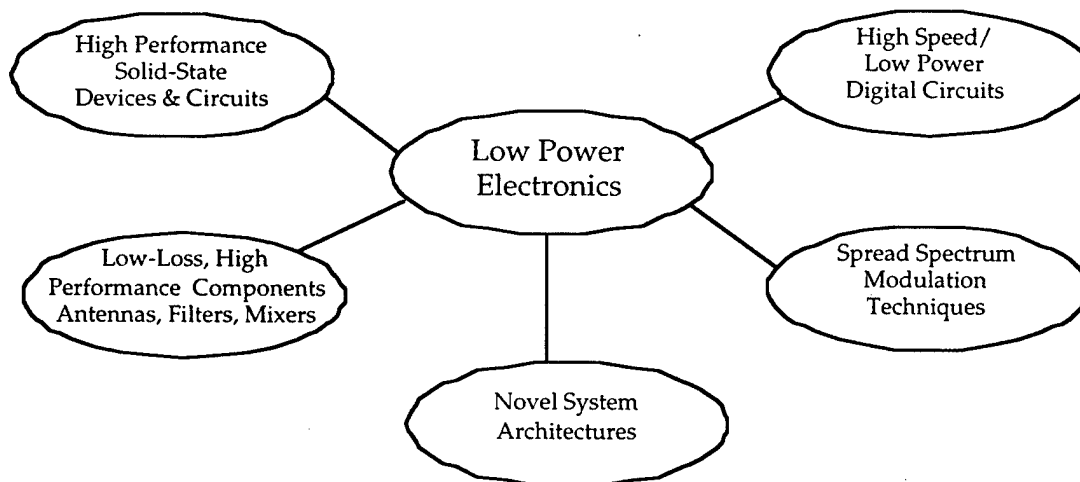


Figure 2

Some of the generic issues that have been addressed which are essential for mobile and low power communication systems include:

- New System Architectures Utilizing New Components
- Spread Spectrum Modulation Techniques
- High Efficiency, High Power Amplifiers
- Low Noise, High Dynamic Range Amplifiers
- Power Management and Dynamic Control of Power, Efficiency and Linearity
- Low Noise Oscillators and Mixers
- Low-Loss, Very High Q Filters at R. F. and I. F. Frequencies
- Low-Loss, Low Power Switches
- Monolithic Integration of Components and Circuits
- Digital Circuit Optimization and Utilization of New Technologies for Implementation

In order to address these issues a multidisciplinary team of faculty members and graduate students was assembled and several tasks were formulated. These included the following tasks:

***Task I: System Architecture***

- Examine Various System Architectures and Compare Performance Relative to Power Consumption and Identify Problems and Limitations
  1. Superheterodyne
  2. Direct Conversion
  3. Direct Sampling
  4. MEMS-Based Architecture
- Develop Coded-Modulation Techniques for Interference Limited Channels and Determine the Tradeoffs Between Transmit Power and Processing Power Needed for a Given Performance. Which Coded/Modulated/ Spreading Combination is Optimal?

1. Direct-Sequence
2. Frequency-Hopping
3. Multi-Carrier Modulation

Faculty: Professors W. Stark, C. Nguyen, G. Rebeiz and P. Mazumder

***Task II: Spread-Spectrum Modulation Techniques and Sensitivity to Power Amplifiers Nonlinearities***

- Effects of Power Amplifier Nonlinearities on Different Coded-Modulation Schemes
- Comparison of Different Classes of Amplifiers (A,B, F, etc.) Relative to Interference.
- Automatic Control of Efficiency, Linearity and Power Output in Amplifiers

Faculty: Profs. W. Stark and G. Haddad and Drs. J. East and K. Yang

***Task III: High Efficiency Power Amplifiers***

- Devices: HFET's and HBT's
- Nonlinear Models Including Harmonics
- Classes of Operation (B, C, E, F) and Tradeoffs Between Efficiency, Power and Linearity
- Circuit Design and Optimization
- Integration with Antennas
- Frequency Range: 1-60 GHz

Faculty: Profs. G. Haddad and D. Pavlidis and Drs. J. East and K. Yang

***Task IV: InP Devices and Mixed Mode Monolithic Integrated circuits for Low-Power Transceiver Applications***

- HBTs for Low Noise Oscillators and High Efficiency/Linearity Power Amplifiers (SHB and DHBT's)
- HEMT's for LNA's and High Efficiency PA's

- Passive Devices: InGaAs-PIN Diodes for Switches and Heterojunction Schottky Diodes for Mixers
- Circuit Design and Optimization

Faculty: Profs. D. Pavlidis, P. Bhattacharya and G. Haddad and Drs. J. East and K. Yang

*Task V: Low-Loss, High Performance Microwave Components*

- Micromachining Technology
- High Performance Transmission Media
- High Efficiency Antennas
- Low-Loss Resonators, Filters, Multiplexers, etc.
- High Performance Mixers
- High Isolation Packaging Technology
- High Frequency Lumped Elements
- High Q MEMS Filters and Resonators

Faculty: Profs. L. Katehi, G. Rebeiz and C. Nguyen

*Task VI: Digital Circuits*

- Tradeoffs for Different Modulation Techniques
- Tradeoffs Between Analog/Digital Implementations
- Comparison of Various Technologies to CMOS for High-Speed and Power Consumption (HEMT, HBT, C-GaAs, C-InGaAs, NDR-Based Circuits, Q-MOS, etc.)
- Design and Testing of Basic Gates to Demonstrate Performance
- Cooperate with Industry for Larger Demonstration Circuits

Faculty: Profs. P. Mazumder, W. Stark and G. Haddad and Dr. J. East



## Summary of the Most Important Results

- \* Proposed and investigated a new system architecture based on MEMS technology which can result in immense power reduction.
- \* We have quantified the performance gains possible with dual-bias control amplification for a centralized system and have shown a factor of 10 reduction in required energy with dual-bias techniques compared to conventional techniques.
- \* Developed a subharmonic double balanced RFIC mixer which will have a significant impact on power consumption.
  - For use in dual frequency systems
  - For realizing direct conversion receivers
- \* Evaluated the impact of new device technology on digital circuit performance relative to power consumption and frequency/speed performance (RTD/HBT, RTD/HEMT and Q-MOS).
- \* Developed an analytical technique for estimating the effect of amplifier nonlinearity on different coded modulation techniques in order to quantify the tradeoffs between spectral and power efficiency.
- \* Developed an experimental system that can measure the effect of amplifier operation on different modulation waveforms.
- \* Used the system to measure AM-AM and AM-PM, multitone IP3 and arbitrary modulation waveforms in a single setup.
- \* Investigated power amplifier schemes based on dual digital and analog bias control for efficiency and linearity enhancement.
- \* These schemes can result in significant efficiency improvement of power amplifiers (factors of 2 or more).
- \* Proposed a new performance measure to optimize power amplifiers for different modulation schemes in a unified way.
- \* Quantified and optimized the performance and power consumption of OFDM systems with recently proposed dc bias controlled amplifiers.
- \* Analyzed the effect of a nonlinear amplifier on the bit error rate performance of single cell convolutionally coded multicarrier-code division multi-access systems in the presence of multipath fading.

- \* Completed the implementation of the large signal time domain active load pull system and used it for characterization of FET's.
- \* Developed design procedures and compared the characteristics of various modes of operation for power amplifiers relative to power output, gain, efficiency and linearity (class A, B, E, F, etc.)
- \* Developed design procedures for microwave circuit analysis and design for high efficiency amplifiers.
- \* A 5 GHz class-E power amplifier using Fujitsu FLK052 device produced 72% PAE, 81% drain efficiency and 610 mW output power with 9.8 dB saturated gain at a drain bias of 8V.
- \* A 8.3 GHz class-F power amplifier using Fujitsu FLK052 device produced a PAE of 60%, drain efficiency of 72% with an output power of 685 mW and a saturated gain of 7.4 dB. This is the frequency limit for suboptimal switched mode operation for this device.
- \* A 8.3 GHz class-E power amplifier using Fujitsu FLK202, a 4 times larger device in terms of gate periphery when compared to the same intrinsic FLK052 device, produced 1.7 W of output power with 50% PAE, 68% drain efficiency and a saturated gain of 5.3 dB.
- \* Investigated and optimized high-efficiency frequency multipliers that have conversion gain
- \* Demonstrated record performance for PNP InP HBTs  $f_t = 13$  GHz,  $f_{max} = 35$  GHz,  $P_{out} = 0.5$  mW/ $\mu\text{m}^2$  at 10 GHz  $G = 10$  dB and PAE = 24%
- \* Demonstrated for the first time integrated NPN-PNP push-pull amplifiers for high linearity/efficiency operation.
- \* Developed small- and large-signal models for NPN and PNP HBTs for mixed mode circuit design.
- \* Evaluated the feasibility of InP-based mixed-mode technology for low-power, high linearity, high efficiency transceiver applications
- \* Designed and fabricated a special mask set for studying growth and device fabrication of dissimilar device structures integrated on a common InP substrate (HBT, HEMT, mixer diodes, etc.)

- \* Grew HEMT and HBT layers by MBE and MOCVD and initiated studies of individual vs. stacked growth of devices: fabricated and evaluated D.C. and microwave characteristics of stacked HEMT/HBT/PIN designs (Results are very encouraging)
- \* Achieved record performance in high frequency micromachined filters and MEMS switches and low frequency MEMS filters and mixers.
- \* Proposed, and demonstrated a novel circuit topology for an RFIC subharmonic double-balanced mixer. This is significant for low-power direct conversion receivers and dual frequency systems. Performance compares favorably with conventional double-balanced mixer.

Typical results include:

#### Membrane Filters

- 3% at 37 GHz with 2.3db Ins. loss
- 8% at 60 GHz with 1.5db Ins. loss
- 3% at 62 GHz with 3.1db Ins. loss
- Monolithic integration: microstrip or CPW feed

#### Micromachined Cavity Filters

- Q up to a few thousands (highest measured of 1100)
- Narrow bandwidth (lowest measured 2.5%)
- Low insertion loss (0.5 db for 4.5% BW at 10 GHz)
- Monolithic integration: microstrip or CPW feed

- \* High frequency MEMS switches
  - Development of an architecture that has demonstrated less than 0.2 dB insertion loss up to 40 GHz
  - Low power (1-5  $\mu$ W)
  - Switching speed (tens of  $\mu$ s)
  - Air bridge switch (0.3 db insertion loss, 45 db isolation at 30 GHz. Moderate BW)
  - Compliant switch (0.1 db insertion loss @ 20 GHz and 38 db isolation, high BW (1-40 GHz)
  - Activation voltage as low as 14 V (with the potential to reduce it to 5V)

- \* Low frequency MEMS filters and mixers
  - Demonstrated a second-order 34.5 MHz band pass filter with a tunable center frequency of up to 5% (1.3% BW; 2db I.L.)
  - Demonstrated High-Q resonators with frequencies up to 71 MHz ( $Q \approx 9,000$ )
  - Invented and demonstrated a mixer and filter which would allow significant power reduction in the mixer stages
- \* Implemented switchability and unability in VHF micromechanical filters up to 70 MHz.
- \* Investigated via simulation the use of banks of tiny, passive micromechanical filters to realize an RF channel-select receiver architecture capable of orders of magnitude power reduction by trading power for selectivity in frequency hopping architectures.
- \* Demonstrated a virtually levitated resonator design that ideally eliminates anchor losses by supporting a free-free beam resonator at node points with support geometries chosen so that zero impedance is presented to the resonator at attachment locations. Such resonators have been demonstrated up to 93 MHz with Q's still around 8,000, and no sign of Q-reduction with increasing frequency. Performance at this level and at these frequencies is sufficient to satisfy requirements for SINCGARS radios and may very well be able to greatly alleviate co-site problems in UAV's.
- \* Demonstrated micromechanical mixer+filter+gain devices based on micromechanical resonators. Mixing in these devices is accomplished via a square law voltage-to-force transfer function in the electromechanical transducer for the device. Gain is accomplished parametrically.
- \* Demonstration of high-Q micromechanical resonators operating at frequencies up to 59 MHz.
- \* Low noise oscillators and micromachined circuits
  - Developed a high-Q electromagnetic micromachined resonator on membrane for 20-60 GHz applications with a measured Q of 500-600 at 30-60 GHz
  - Developed a micromachined low loss 28/31 GHz diplexer with more than 50 dB isolation between the transmit and receive band and around 1 dB of loss in the transmit band

- Developed a low phase noise oscillator based on a high-Q micromachined resonator at 28 GHz, with a performance compatible with DRO at 30 GHz
- \* Double-Balanced Mixers
  - Invented a novel double balanced subharmonic mixer for RFIC direct conversion receivers at 1-5 GHz, and implemented a design at 1.9 GHz using MAXIM SiGe process
  - Invented a novel balanced doubler with more than 40 dB harmonic rejection without the use of any external filtering techniques, resulting in a very compact circuit.
- \* Development of spectral techniques for low-power synthesis.
- \* Identification and analysis of quantum MOS circuit technology for low-power circuit design.
- \* Design of a low-power numerically controlled oscillator (NCO).
- \* Design of a low-power 32-bit correlator chip.
- \* Design of a low-power, high-speed modulator 4-bit turbo-code decoder.
- \* Design of a low-power, high-speed sense amplifier for memories required in communication circuit systems.
- \* Design of ultrafast and compact edge-triggered circuits for peripheral circuitry of communication systems.
- \* Fabrication of QMOS chip prototype.
- \* Development of a quantum circuit prototyping methodology using generic CMOS process.

Many other important results have been summarized in the annual reports, the various publications, and several chapters in a new book dedicated to the work under this program, which was recently published by Wiley, entitled "RF Technologies for Low Power Wireless Communications," edited by T. Itoh, G. Haddad and J. Harvey.

## Publications and Technical Reports Supported

### a) Papers published in peer-reviewed journals

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**b) Papers published in non-peer-reviewed journals or in conference proceedings**

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## 2.0 List of Participating Scientific Personnel

Task	Faculty Members Involved
System Architecture	W. Stark, C. Nguyen, G. Rebeiz, P. Mazumder
Spread-Spectrum Modulation Techniques and Sensitivity to Power Amplifier Nonlinearities	J. East, W. Stark, K. Yang, G. Haddad
High Efficiency Power Amplifiers	J. East, Z. Popovic, K. Yang, D. Pavlidis, G. Haddad
InP Devices and Mixed Mode Monolithic Integrated Circuits for Low-Power Transceiver Applications	D. Pavlidis, P. Bhattacharya, J. East, K. Yang G. Haddad
Low-Loss, High Performance Microwave Components	L. Katehi, G. Rebeiz, C. Nguyen
Digital Circuits	P. Mazumder, J. East, W. Stark, G. Haddad

**Advanced Degrees Earned While Employed on the Project:**

<b><u>Student</u></b>	<b><u>Advisor</u></b>	<b><u>Date of Ph.D.</u></b>	<b><u>Place of Employment</u></b>
G. O. Munns	G. Haddad	1997	APA Optics, Inc.
Gildas Gauthier	G. Rebeiz	1998	Thompson-CSF, France
James Kempf	G. Haddad	1999	Texas Instruments
Eric Bryerton	Z. Popovic	1999	National Radio Astronomy Observatory
Donald Sawdai	D. Pavlidis	1999	TRW
Saeed Mohammadi	D. Pavlidis	1999	University of Michigan
Andrew Brown	G. Rebeiz	1999	REMEC
Shriram Kulkarni	P. Mazumder	1999	IDT
Je-hong Jong	W. Stark	2000	Hughes Network Systems
Vuk Borich	G. Haddad	2000	Applied Wave Research, Inc.
Jae-Woo Park	D. Pavlidis	2000	Knowledge-On
Sergio Pacheco	L. Katehi	2001	Motorola
Delong Cui	D. Pavlidis	2001	Ciena
T. Nolan	W. Stark	2001	Harris

## Report of Inventions

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